MEMS Sensing & Actuation

Lecture 11

Class QUIZ (a) identify and (b) model, the system

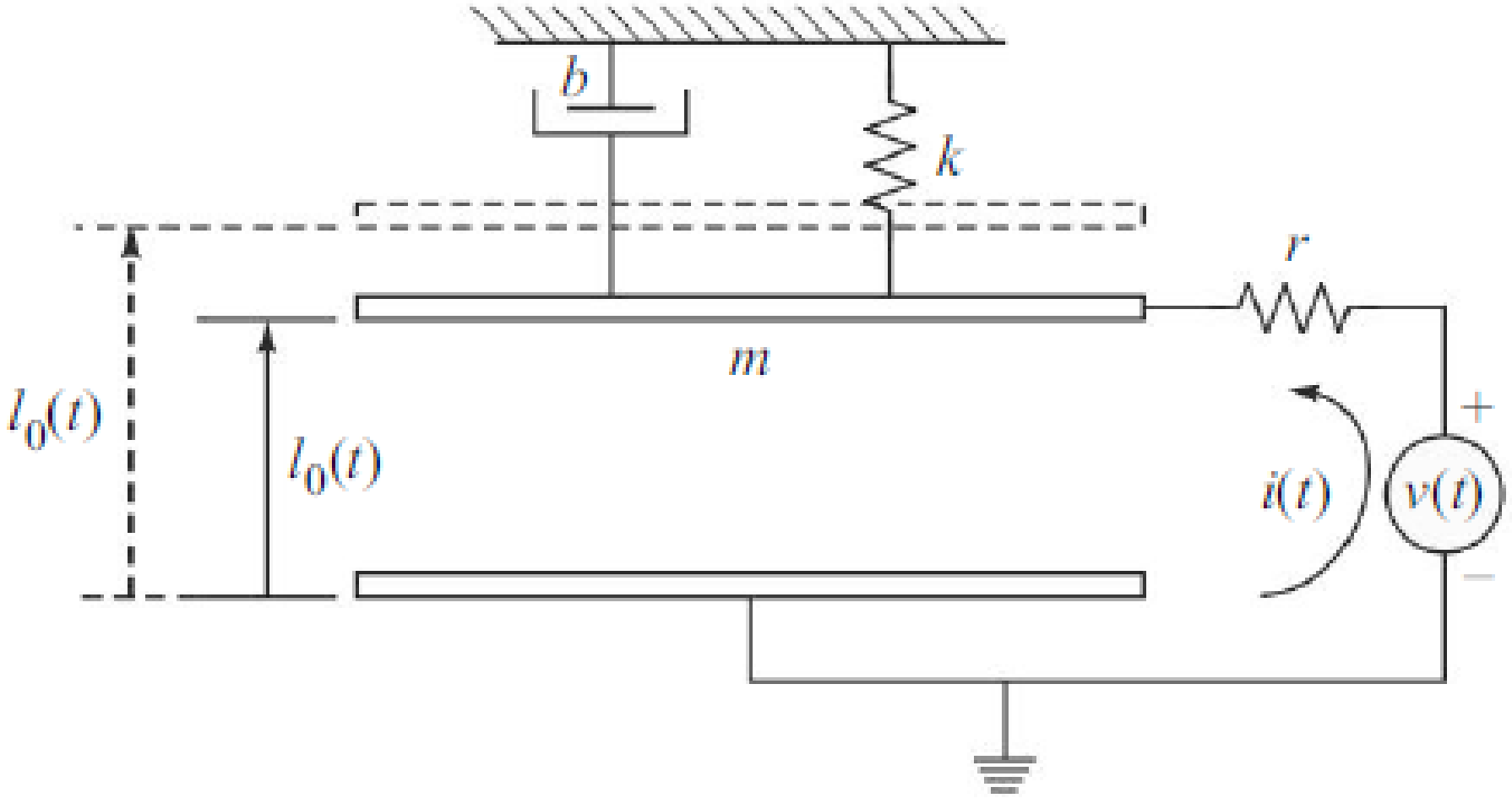


Table 3.3 *Basic modeling elements of the systems*

Engineering systems	*Energy source (Means of supplying energy)*	*Basic modeling elements*	*Energy stored/Power loss*
Mechanical	• Force	Translational spring	Translational = $\frac{1}{2}kx^2$
	• Velocity	Rotational spring	Rotational = $\frac{1}{2k_a}T^2$
		Translational damper	Power loss = $b_t v^2$
		Rotational damper	Power loss = $b_r w^2$
		Mass/inertia	Translational = $\frac{1}{2}mv^2/$
			Rotational = $\frac{1}{2}Jw^2$
Electrical	• Current	Inductor	$\frac{1}{2}Li^2$
	• Voltage	Resistance	Power loss = $\frac{v^2}{R}$
		Capacitance	$\frac{1}{2}Cv^2$
Fluid	• Fluid flow	Inertance	$\frac{1}{2}\Gamma Q^2$
	• Pressure	Fluid resistance	$\frac{1}{R_f}P^2$
		Fluid capacitance	$\frac{1}{2C_f}P^2$
Thermal	• Heat flow	Thermal capacitance	$C_t\kappa$
	• Temperature	Thermal resistance	

$$C = \varepsilon A / l(t) \tag{1.1}$$

$$F = Q^2(t) / 2\varepsilon A \tag{1.2}$$

$$i(t) = \frac{1}{R}\left\{v(t) - \frac{Q(t)l(t)}{\varepsilon A}\right\} \tag{1.3}$$

$$ml(t) = -\, bl(t) - k\{l(t) - l_0\} - \frac{Q^2(t)}{2\varepsilon A} \tag{1.4}$$

$$Q(t) = \frac{1}{R}\left\{v(t) - \frac{Q(t)l(t)}{\varepsilon A}\right\} \tag{1.5}$$

where, $v(t)$ = Controlling input voltage; $Q(t)$ = Charge in the capacitor; F = Coulomb force; C = Capacitance; $i(t)$ = Current through resistor; $l(t)$ = Air gap; l_0 = Initial gap (when $v(t)$ is zero); A = Plate area; ε = Permittivity in the air gap; R = Resistance in the circuit; m = Mass of the top plate; b = Damping constant; and k = Spring constant

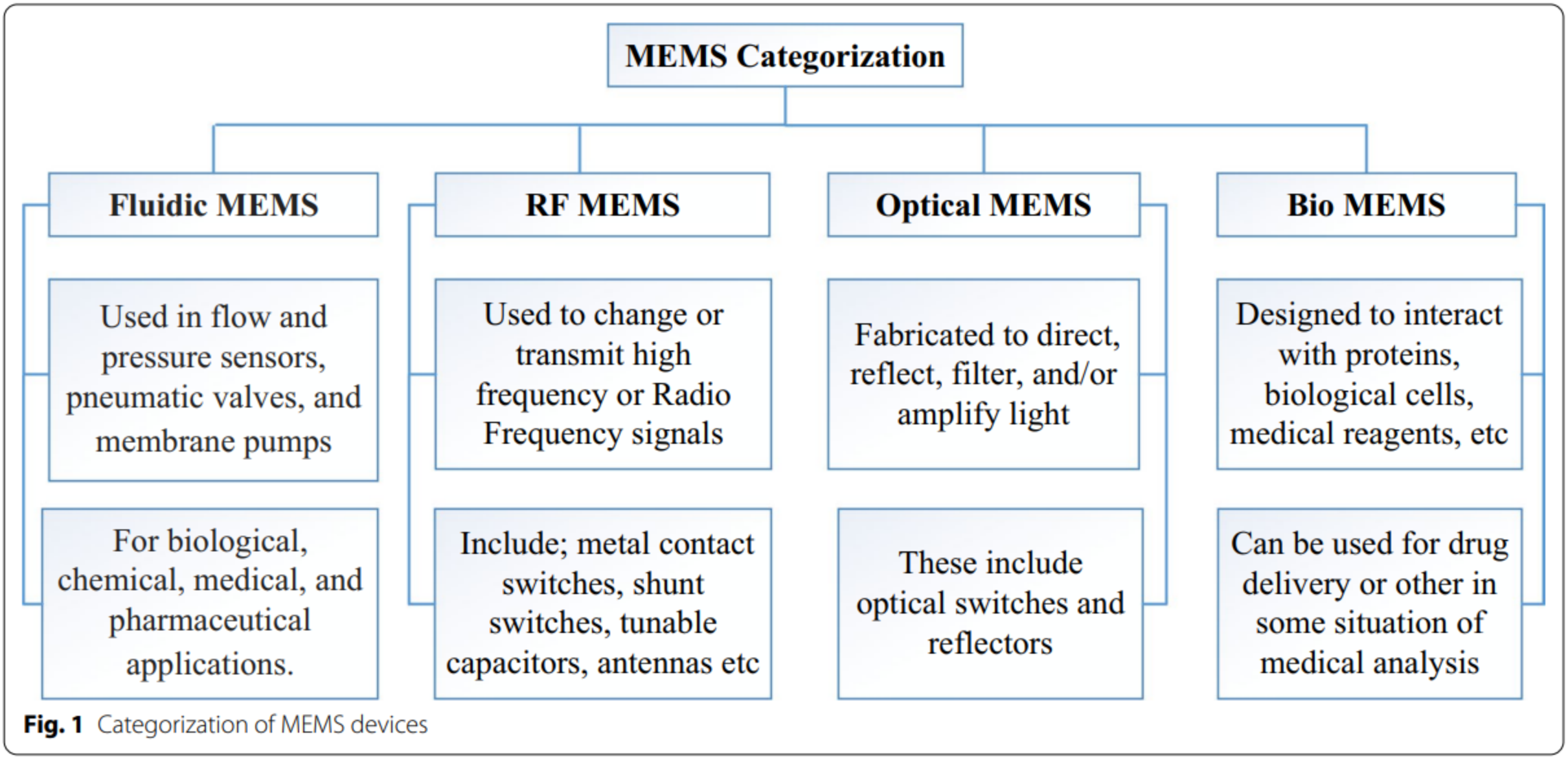

MEMS Categorization
Fluidic MEMS
RF MEMS
Optical MEMS
Bio MEMS
Used in flow and pressure sensors, pneumatic valves, and membrane pumps
Used to change or transmit high frequency or Radio Frequency signals
Fabricated to direct, reflect, filter, and/or amplify light
Designed to interact with proteins, biological cells, medical reagents, etc
For biological, chemical, medical, and pharmaceutical applications.
Include; metal contact switches, shunt switches, tunable capacitors, antennas etc
These include optical switches and reflectors
Can be used for drug delivery or other in some situation of medical analysis

Fig. 1 Categorization of MEMS devices

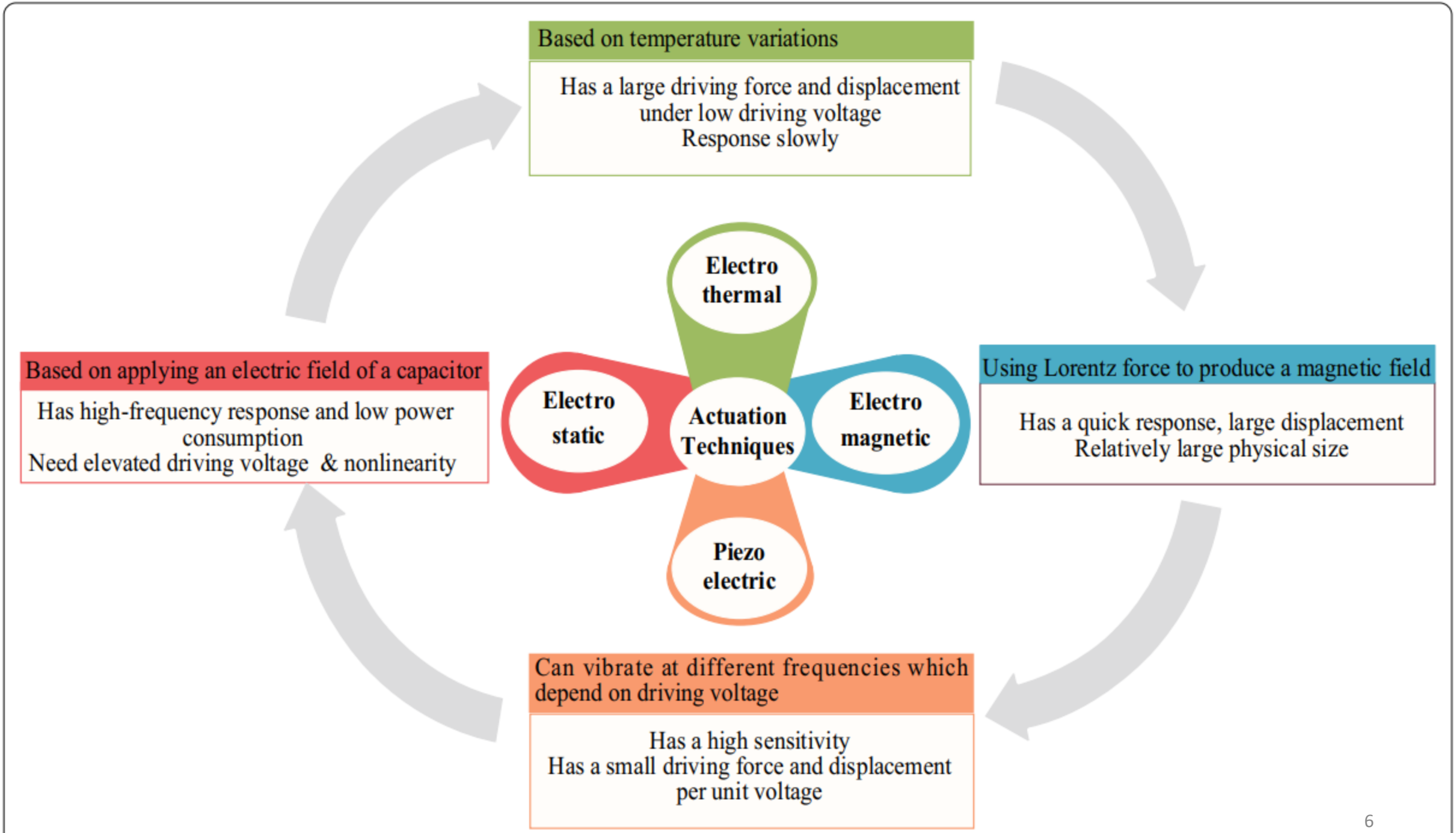

Based on temperature variations
Has a large driving force and displacement under low driving voltage
Response slowly
Using Lorentz force to produce a magnetic field
Has a quick response, large displacement
Relatively large physical size
Can vibrate at different frequencies which depend on driving voltage
Has a high sensitivity
Has a small driving force and displacement per unit voltage
Based on applying an electric field of a capacitor
Has high-frequency response and low power consumption
Need elevated driving voltage & nonlinearity
Electro thermal
Electro magnetic
Piezo electric
Electro static
Actuation Techniques

Fig. 2 Actuation techniques of MEMS-based sensor device

Table 1.3 *Typical power requirements against driving principles*

Driving Method	*Power Usage*	*Voltage range*	*Current range*	*Force generated*	*Deflection range*	*Speed*
Mechanical	High	10–100 V	nA–μA	Moderate	Moderate	mS
Thermal	High	1–10 V	mA–10mA	Moderate	Small	mS
Electrostatic	Low	10–100 V	nA–μA	Moderate	Moderate	μS
Magnetic	Medium	1–5 V	~100 mA	High	Large	μS–mS

Table 2.10 *Bulk versus surface micromachining*

Bulk micromachining	*Surface micromachining*
Aspect ratio (vertical dimensions): Relatively high (One or more wafer thickness)	Vertical dimensions are limited to the thickness of the deposited layers (~2 μm), leading to compliant suspended structures with the tendency to stick to the support
In most situation the machining involves laminating	Surface micromachined device has its built in support and is more cost effective
Large features with substantial mass, thickness and volume	Relatively small features with low mass, thickness and volume
Not very compatible to traditional IC-based technology	Natural but complicated integration with circuitry; Integration is often required due to the tiny capacitive signals
Piezoresistive or capacitive sensing are easier to implement	Capacitive and resonant sensing mechanisms because of easy formation of air gap and cavity
Sawing, packaging and testing are difficult	No excuse
Substrate are susceptible to fragile near the end of the production	Cleanliness is severely critical near the end of the micromachining process
The technology is relatively matured: Abundance of products and producers	Relatively new technology for which no mature products and producers are available. But building momentum
Utilizes both sides of the substrate; Especially during the process of etching	Several thin film deposition and etching are required to build up 3D microstructures

Source: Adapted from H Jerman, Canada

Draw schematic of parallel plate capacitor for electrostatic actuation

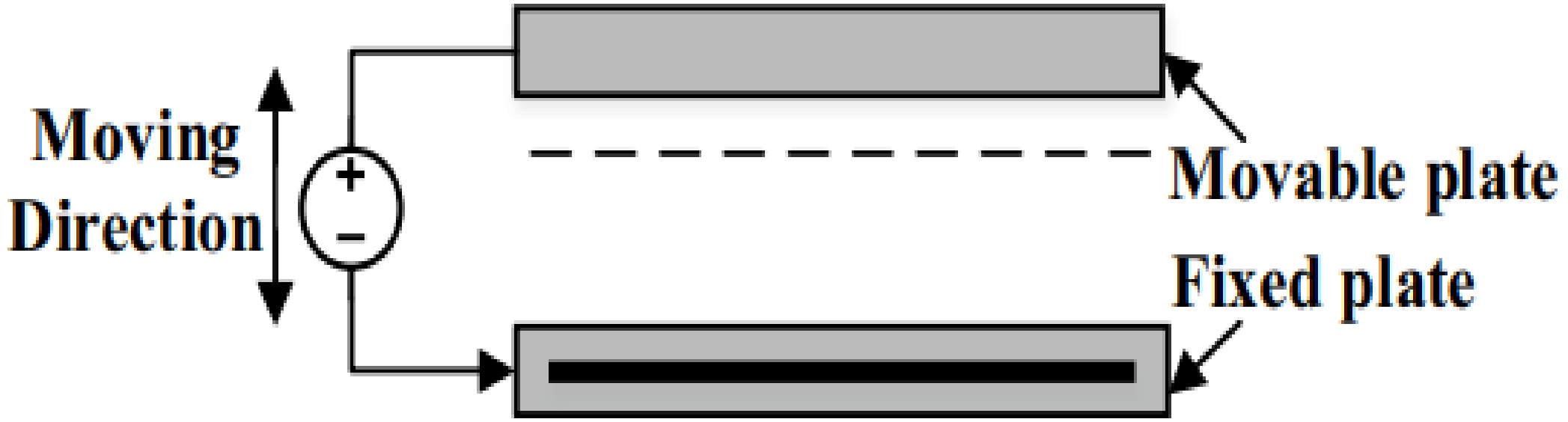


Fig. 3 Parallel plate capacitor for the electrostatic actuation [75]

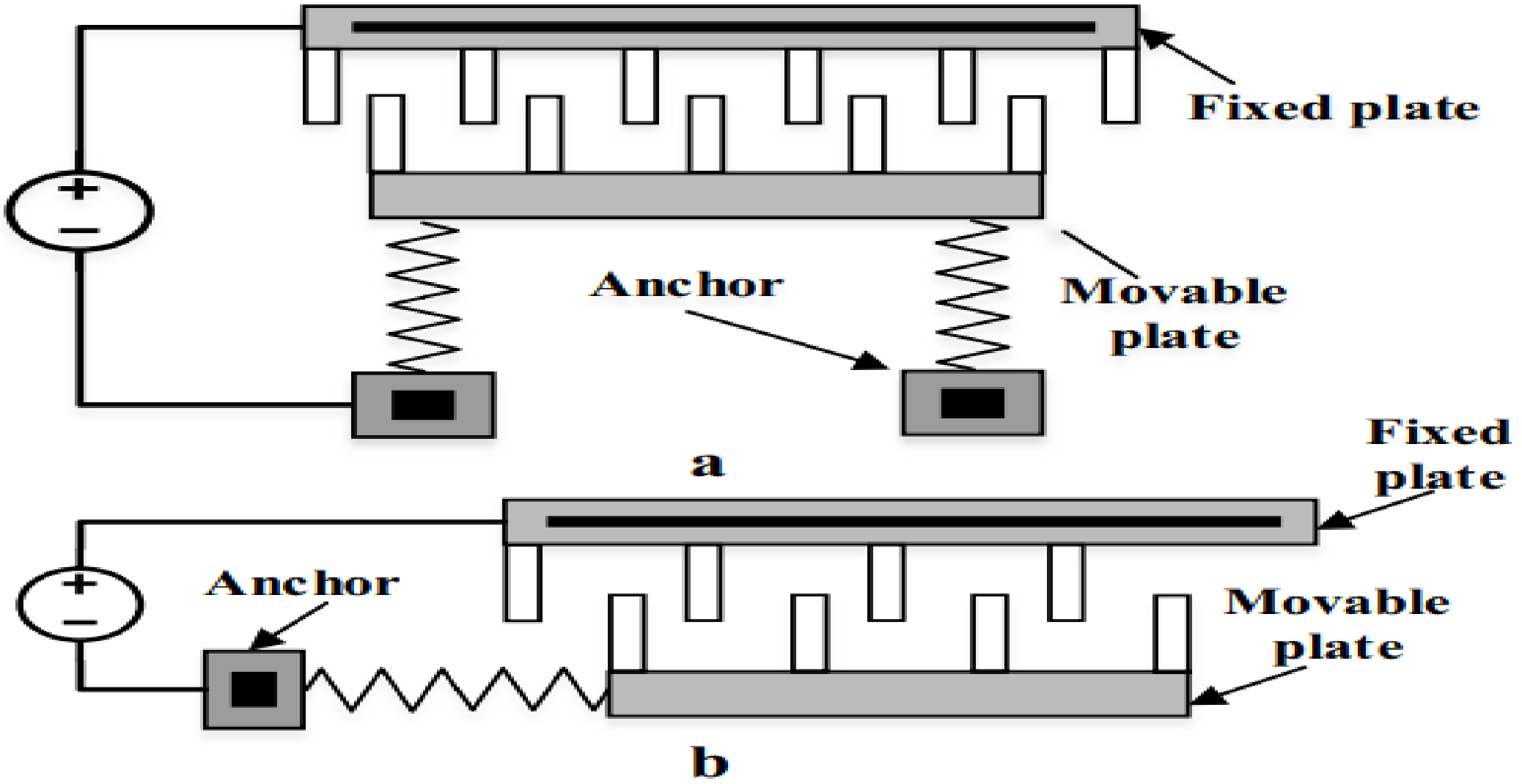


Fig. 4 Schematic of the electrostatic comb-drive configurations [84, 85], **a** longitudinal interdigitated comb actuator; **b** transverse actuator

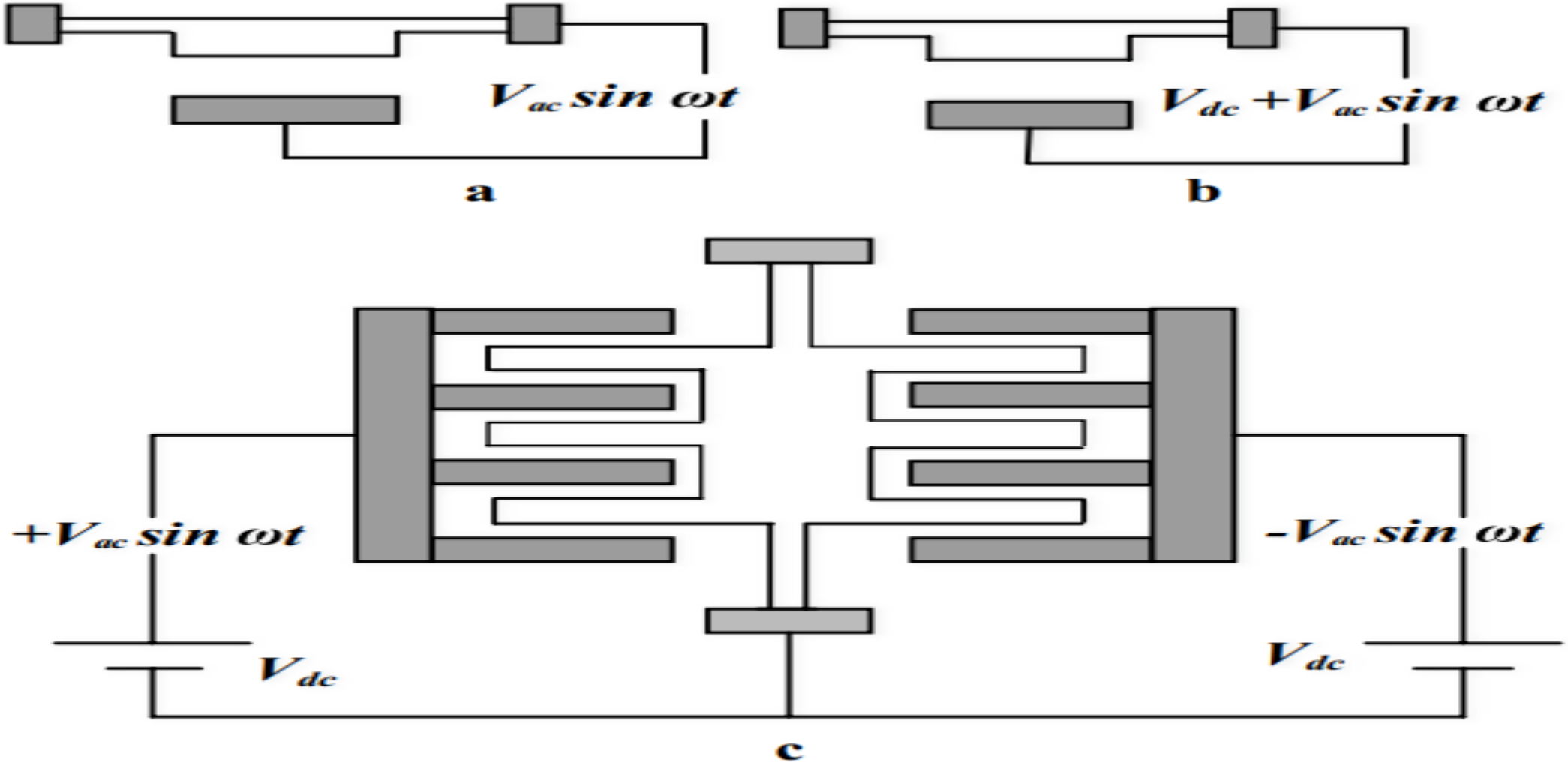


Fig. 5 Comb driving resonator **a** Simple alternative voltage driving, **b** alternating voltage with a dc bias, and **c** push–pull driving scheme [86]

Draw schematic of electro-thermal actuation

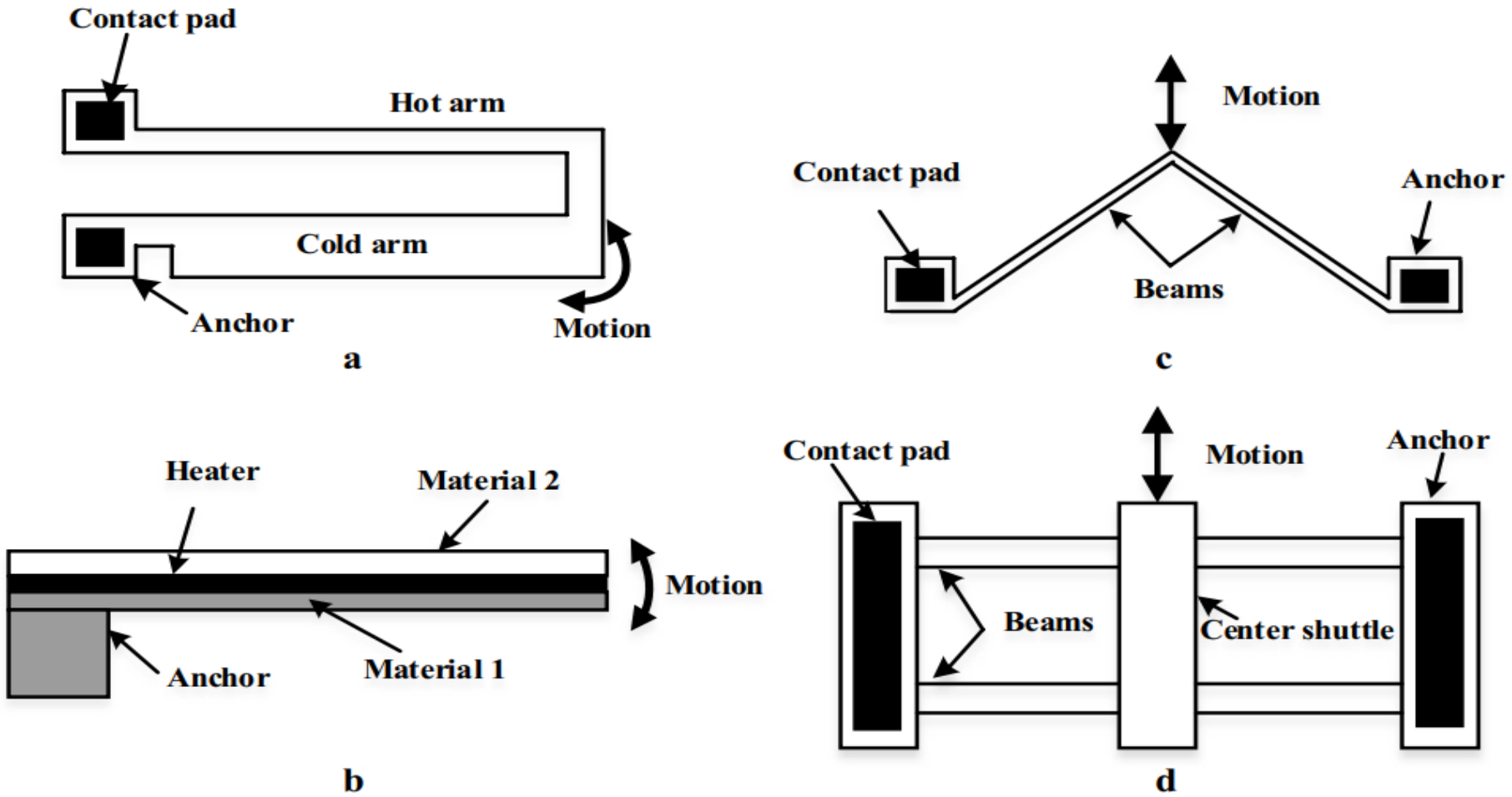


Fig. 6 Schematic of the electrothermal actuation **a** U-Beam Actuator (hot/cold arm), **b** bimorph actuator (Bi-material actuator), **c** and **d** buckling actuators (V-Beam Actuator and shuttle beams) [67, 92]

Draw schematic of electro-magnetic actuation

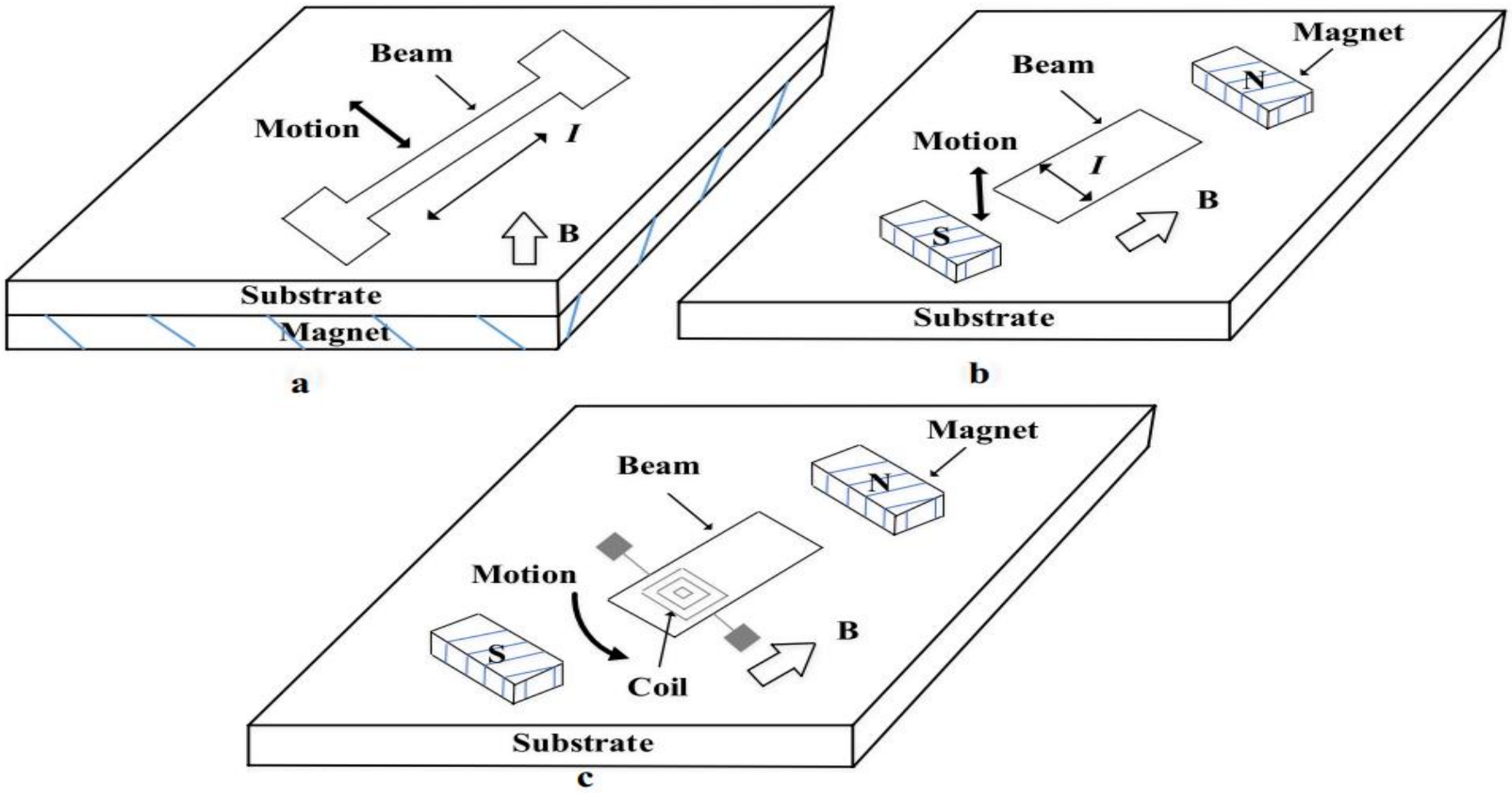


Fig. 7 Schematic of the electromagnetic actuation using Lorentz forces **a** in-plane actuator, **b** and **c** out-of-plane actuator [72]

Draw schematic of piezoelectric actuation

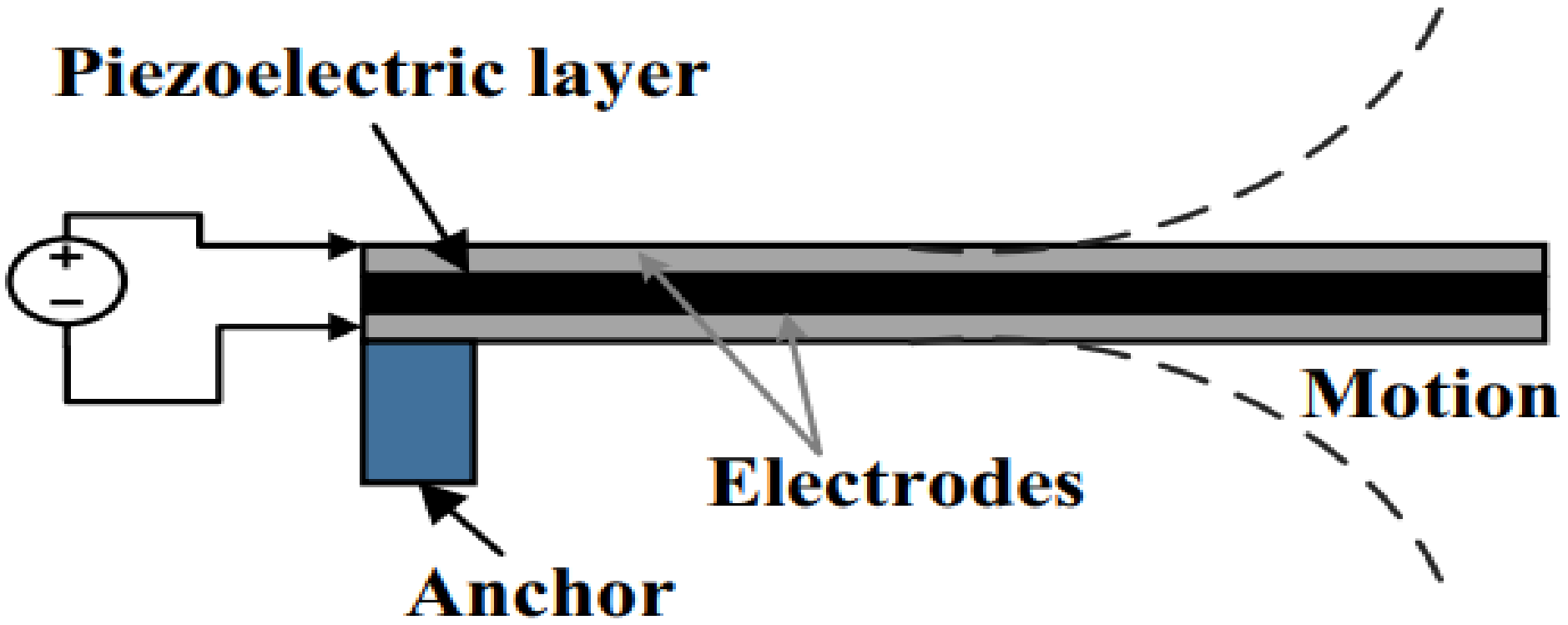


Fig. 8 Schematic of the piezoelectric actuator [72]

Table 2 Summary of actuation mechanisms for MEMS-based sensor devices

Actuation technique	Technology/device	Operation principle	Applications	Year	Refs.
Electrostatic	BioMEMS sensor	Capacitive based Interdigitated electrodes (IDE)	Biosensor application	2019	[56]
Electrostatic	Microcantilever -based MEMS sensors	Capacitive sensing	Humidity Sensor	2019	[57]
Electrostatic	MEMS nanopositioning system	Sigma-delta type arrangement	Nanopositioner	2016	[58]
Electrostatic	Bistable MEMS switch	Pull-in voltage	Switch applications	2016	[59]
Electrostatic	MEMS resonators	Parallel-plate model	closed-loop noise of MEMS oscillators	2016	[60]
Electrostatic	MEMS gyroscope	Comb drives or parallel plate capacitors	Navigation (automobile GPS)	2016	[62]
Electrostatic	CMOS-MEMS resonator	Interdigitated comb actuator	Mass-Sensitive Gas Sensors	2014	[63]
Electrostatic	CMOS-MEMS resonator		Biomarker Detection in Exhaled Breath	2015	[82]
Electrothermal	MEMS-based acetone vapour sensor	Different coefficients of thermal expansion (CTEs)	Diabetes screening	2018	[66]
Electrothermal	CMOS-MEMS device	Different CTEs	Humidity sensing purpose	2017	[4]
Electrothermal	MEMS resonator based filters	U-shape double-clamped beam	Filter components	2016	[67]
Electrothermal	CMOS-MEMS sensor	Different CTEs	Humidity Sensing	2015	[44]
Electrothermal	Tuneable MEMS ring resonator	Different CTEs of materials	Filtering Applications	2015	[68]
Thermo-Electric	MetalMUMPs device	Different CTEs of materials	Out-of-Plane micrometric Displacements	2014	[121]
Thermal actuation	A MEMS-based electrostatic field sensor (EFS)	Clamp-clamp beam	Modulate the external electrostatic field	2014	[122]
Electromagnetic	MEMS actuator	Lorentz force	Optical switches, and micro scanners	2015	[69]
Piezoelectric	Mass-sensor based micro-cantilevers	ZnO thin films	A bio-or chemical event detection	2019	[48]

MEMS Sensing

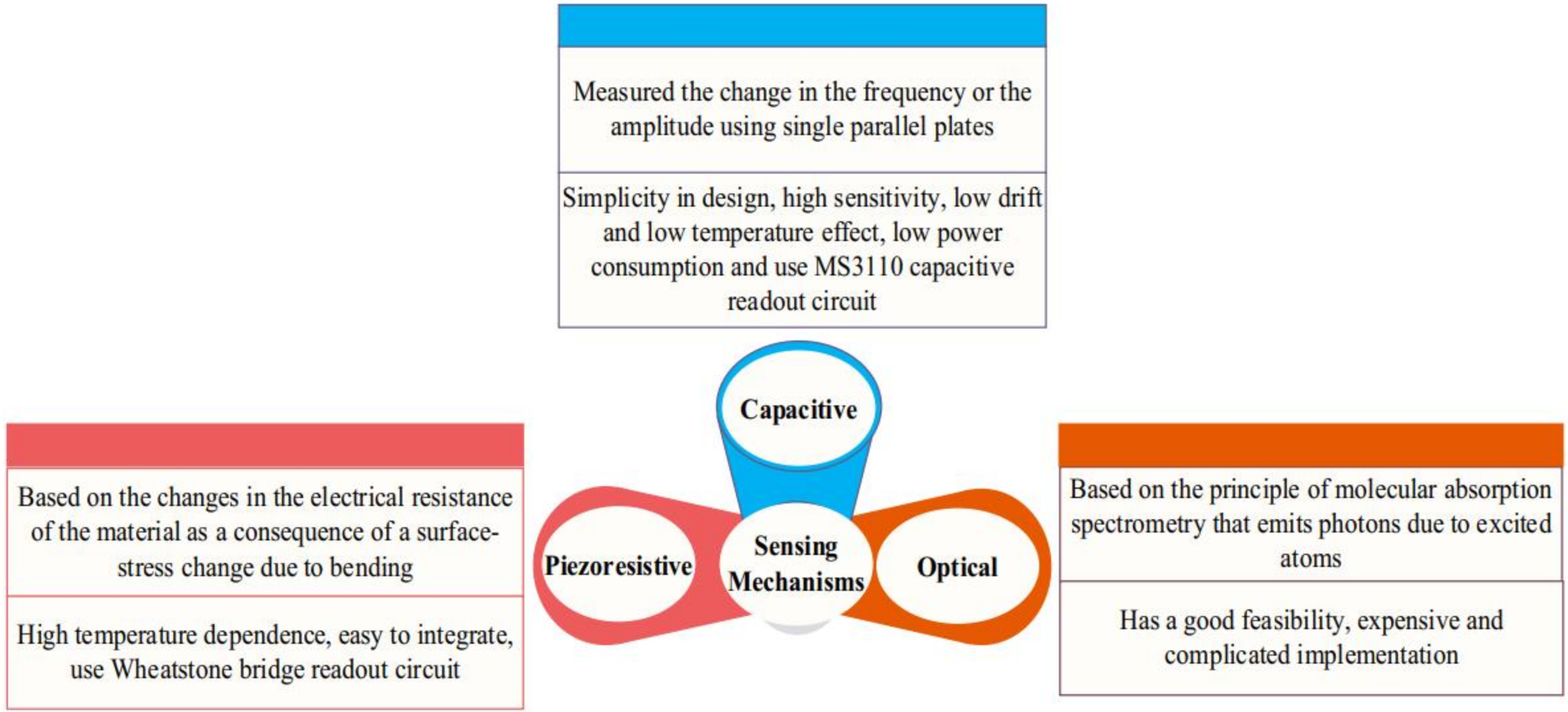

Measured the change in the frequency or the amplitude using single parallel plates
Simplicity in design, high sensitivity, low drift and low temperature effect, low power consumption and use MS3110 capacitive readout circuit
Capacitive
Piezoresistive
Sensing Mechanisms
Optical
Based on the changes in the electrical resistance of the material as a consequence of a surface-stress change due to bending
High temperature dependence, easy to integrate, use Wheatstone bridge readout circuit
Based on the principle of molecular absorption spectrometry that emits photons due to excited atoms
Has a good feasibility, expensive and complicated implementation

Fig. 9 Sensing mechanisms of MEMS-based sensor devices

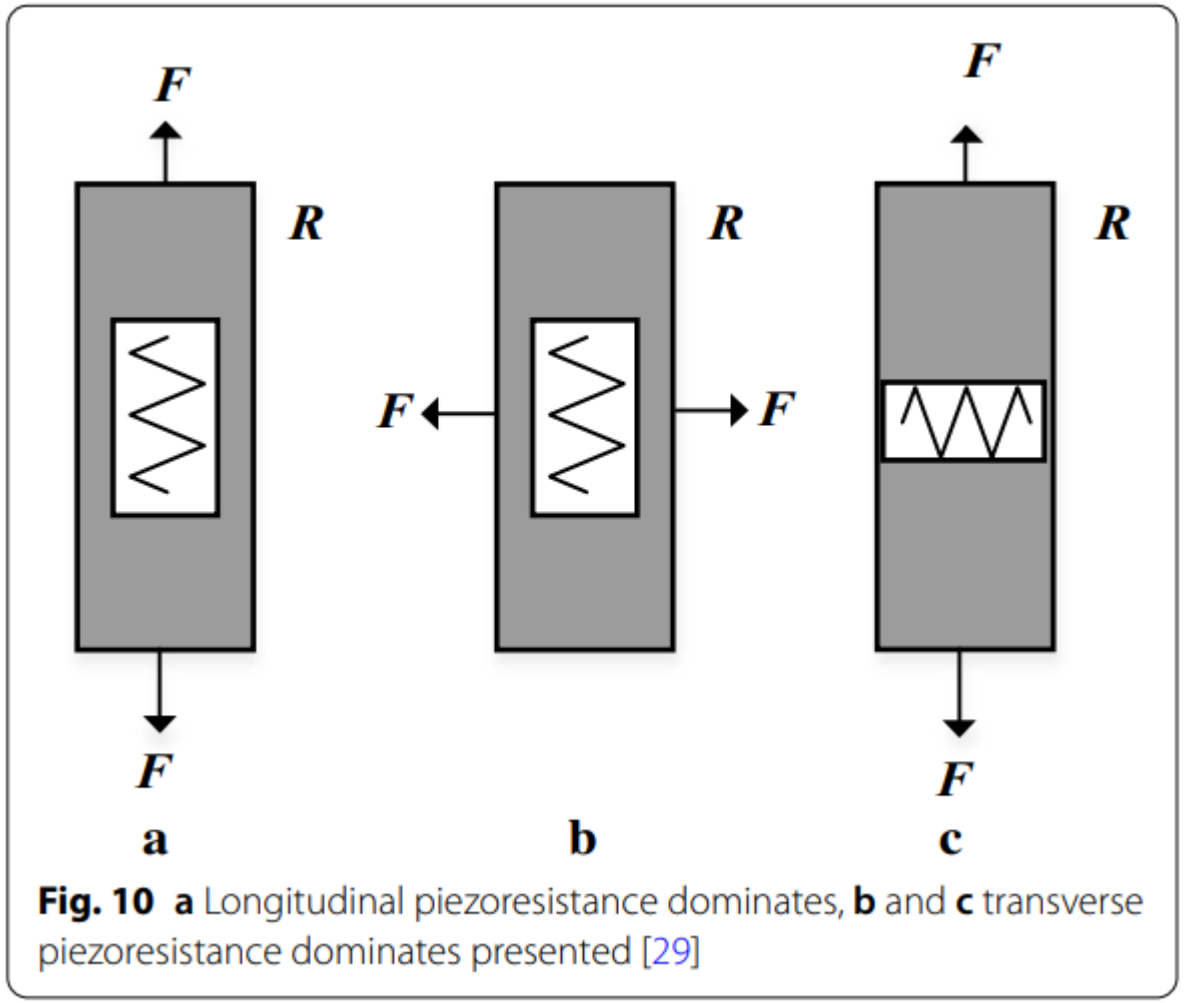
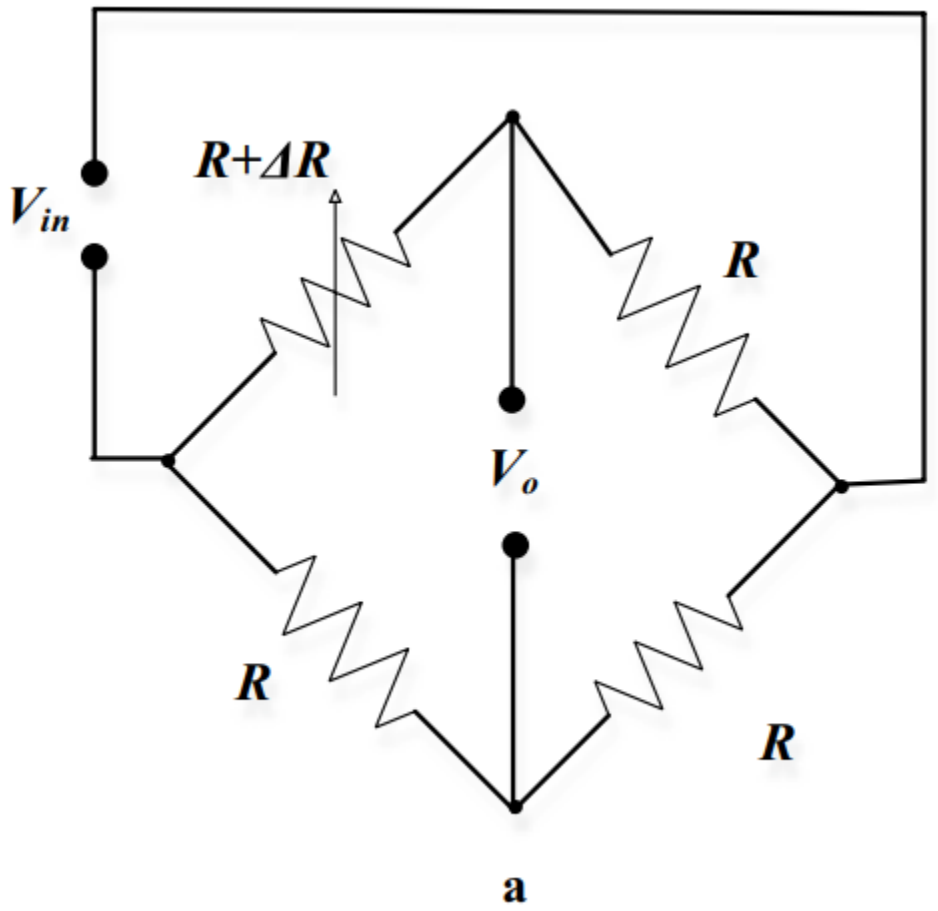
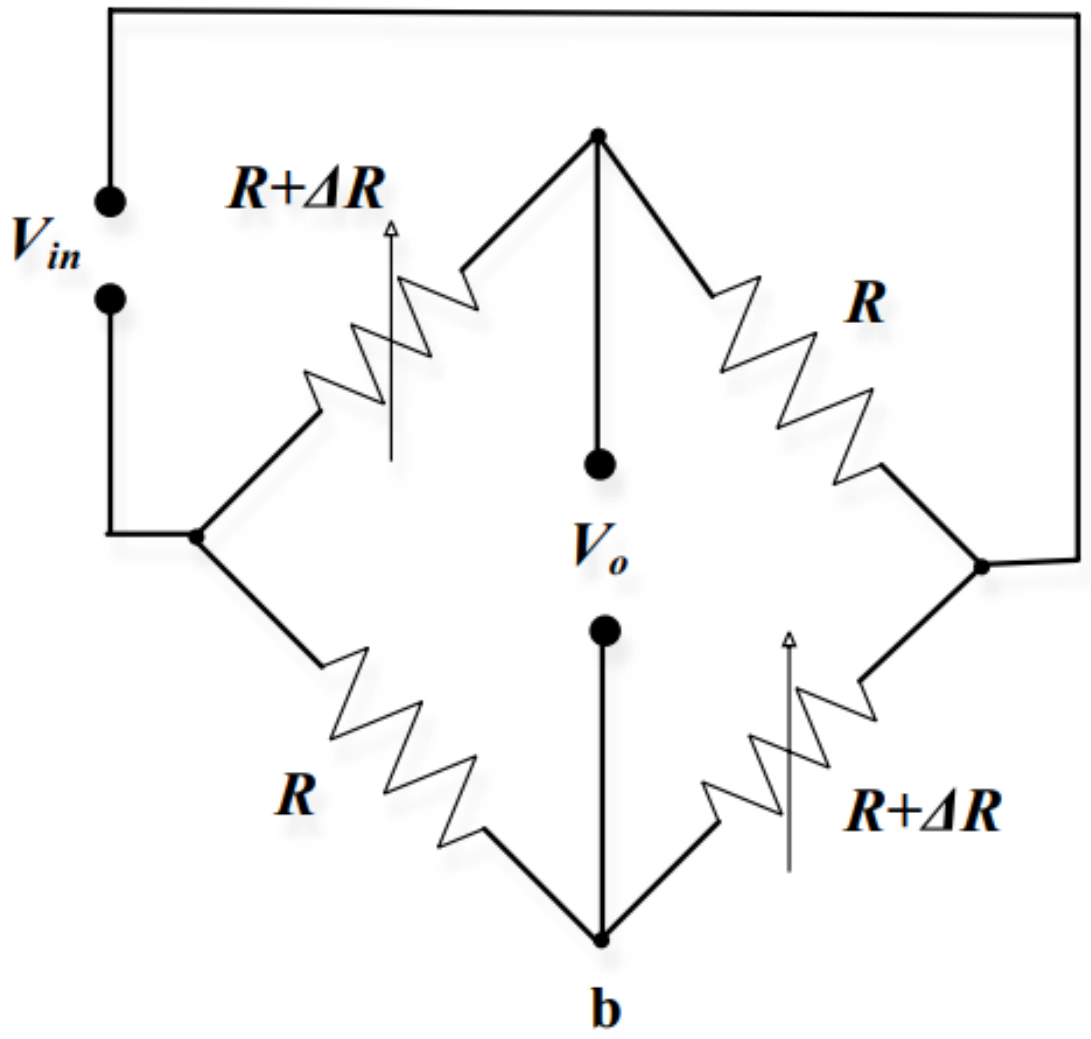


Fig. 10 **a** Longitudinal piezoresistance dominates, **b** and **c** transverse piezoresistance dominates presented [29]

Describe working



Describe working



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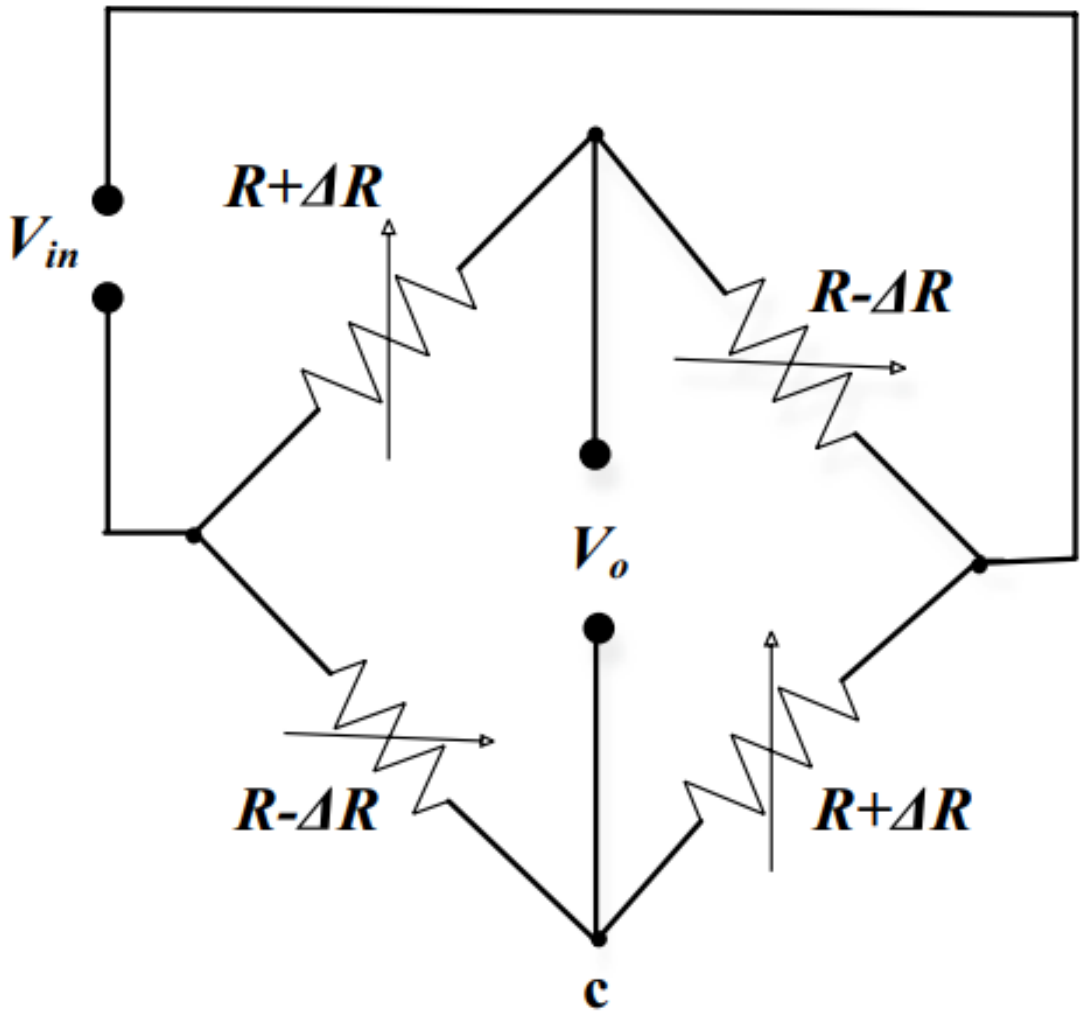

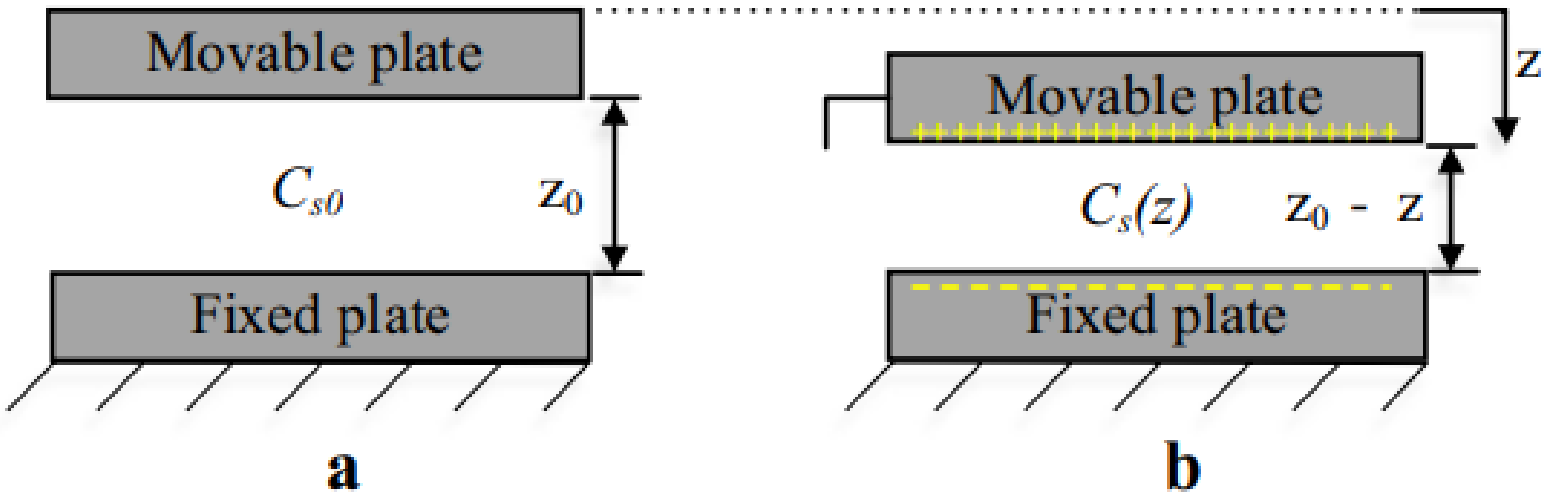

Fig. 12 Parallel plate capacitor showing **a** initial condition and **b** after displacing the movable plate [19]

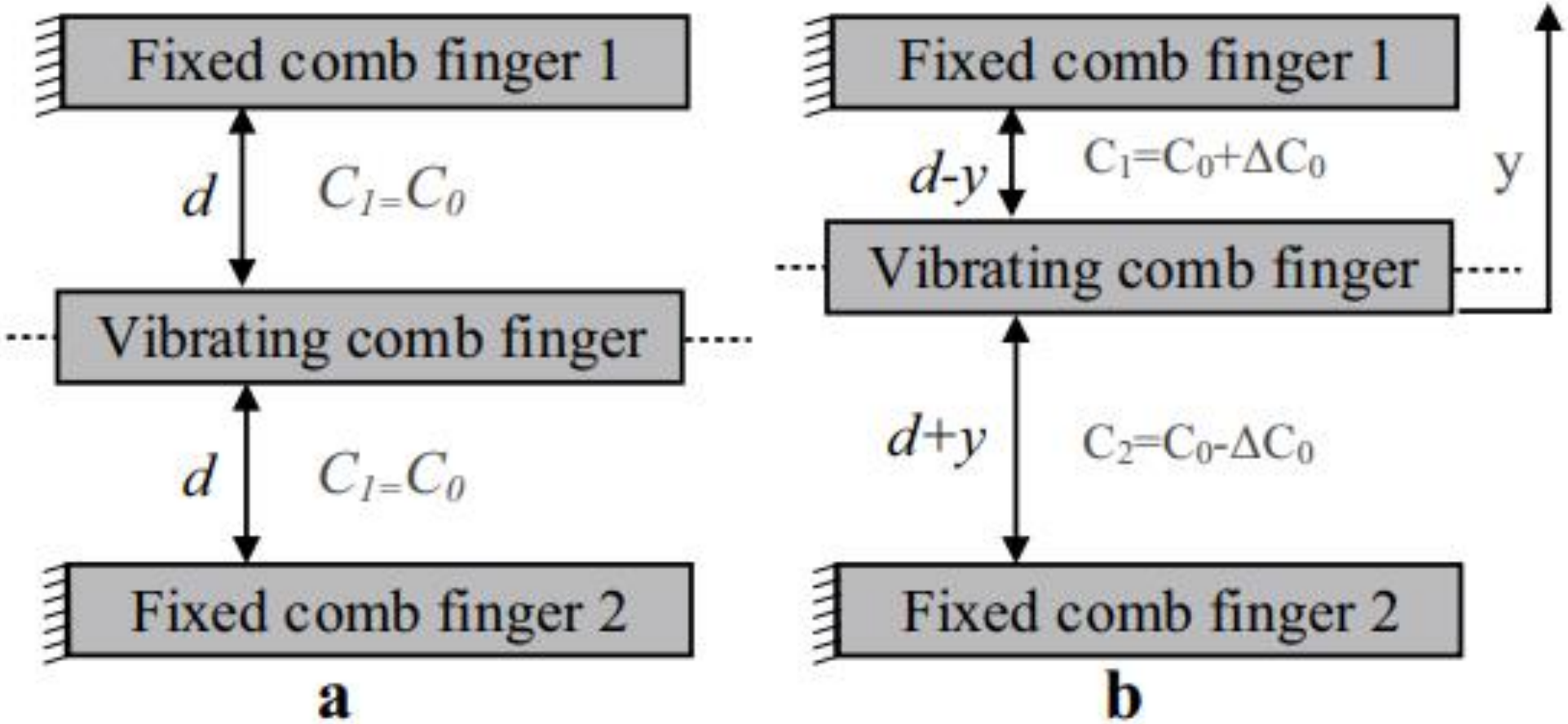

Fig. 13 Comb fingers configuration for MetalMUMPs device showing **a** the initial condition and **b** the displacement of the vibrating comb finger [19]

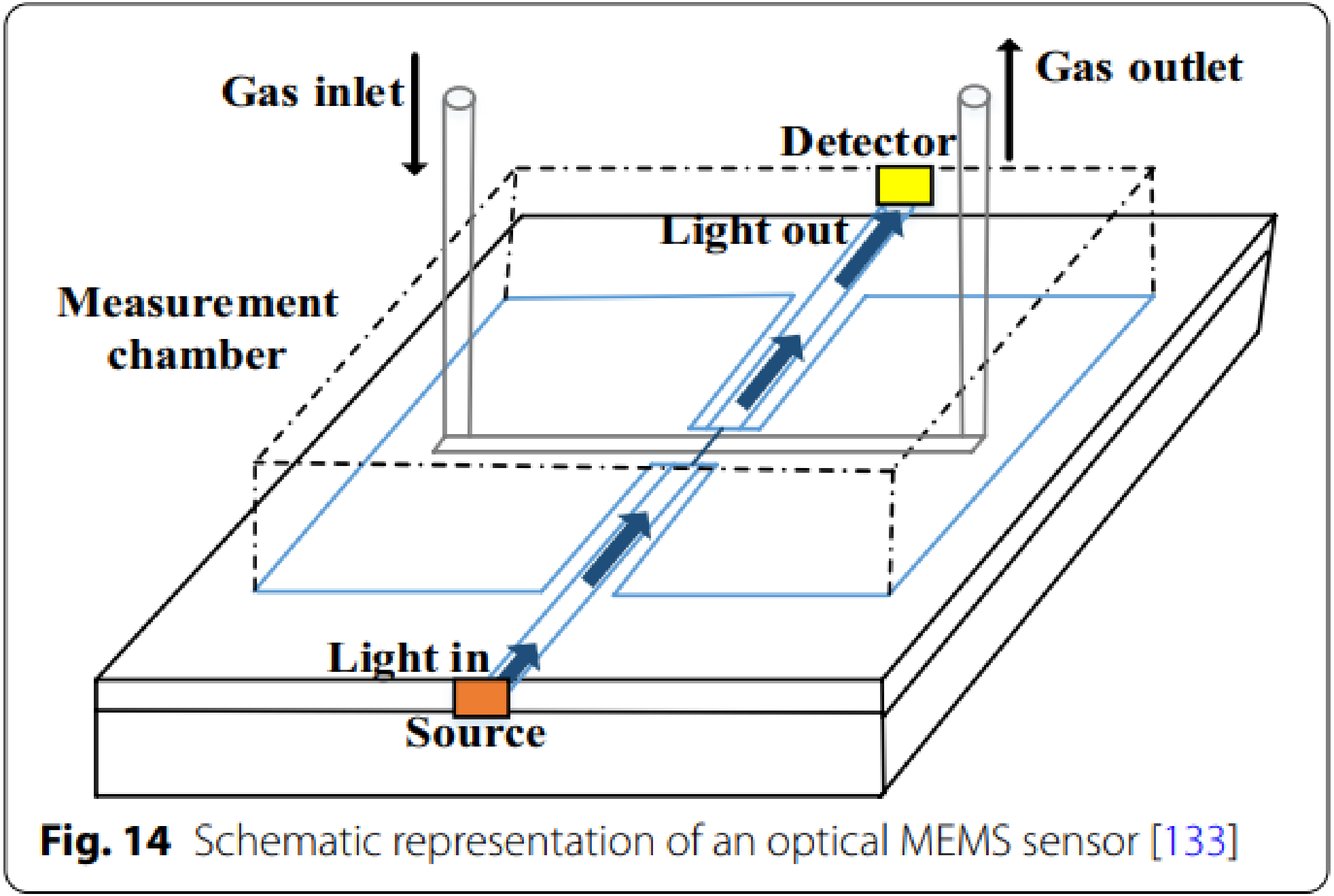

Fig. 14 Schematic representation of an optical MEMS sensor [133]

Table 4 State-of-the-art actuation and sensing mechanisms for MEMS-based sensor devices (N.M not mentioned)

MEMS device	Dennis et al., 2015 [44]	Dennis et al., 2016 [83]	Almur et al., 2017 [104]	Barba et al., 2018 [111]	Mahdavi et al., 2018 [117]	Jiushuai et al., 2019 [112]	Huang et al., 2019 [136]	Zope et al., 2020 [138]
Actuation mechanism	Electrothermal	Electrostatic	Electrothermal	Electromag-netic	Piezoelectric	Electromam gnetic and piezoelectric	N.M	Thermal
Sensing mechanism	Piezoresistive (PZR)	Capacitive	Capacitive	N.M	Thin-film piezoelectric-on-silicon	Piezoresistive	Optical	Piezoresistive
Resonance frequency	2–20 Hz	100–100 kHz	0.5–8 kHz	6.5 kHz	18–20 kHz	18–20 kHz	562.85 Hz	5.13 MHz
Sensitive material	Titanium dioxide (TiO_2) nanoparticles	Chitosan	Chitosan/ polyethylene glycol (PEG) polymers	Boron-doped silicon	ZnO NRs (6 µm/chitosan SAMs)	ZnO NRs (6 µm/chitosan SAMs)	Silicon	Silicon dioxide (SiO_2)
Sensitivity	0.102 mV/% RH to 0.501 mV/% RH	0.042, 0.066, 0.13, 0.18, 0.26 pm/ ppm	0.65 mV/ppm	N.M	16.9–83.3 ppm (30–80%RH, 25 C)	16.9–83.3 ppm (30–80%RH, 25 C)	781.64 nm/g	24.96 kHz/ng
Response time	N. M	N.M	N.M	N.M	46 s/ 167 s	46 s/ 167 s	1.037 µg	7.3 µs
Fabrication technology	CMOS-MEMS	CMOS-MEMS	MetalMUMPs	SOI	N.M	CMOS-MEMS	Bulk silicon process	CMOS-MEMS
Application	Humidity sensing	Screening of diabetes	Acetone vapour sensing	Minimize parasitic phenomena	Dew point meters	Humidity sensing	Inertial navigation	Mass sensing

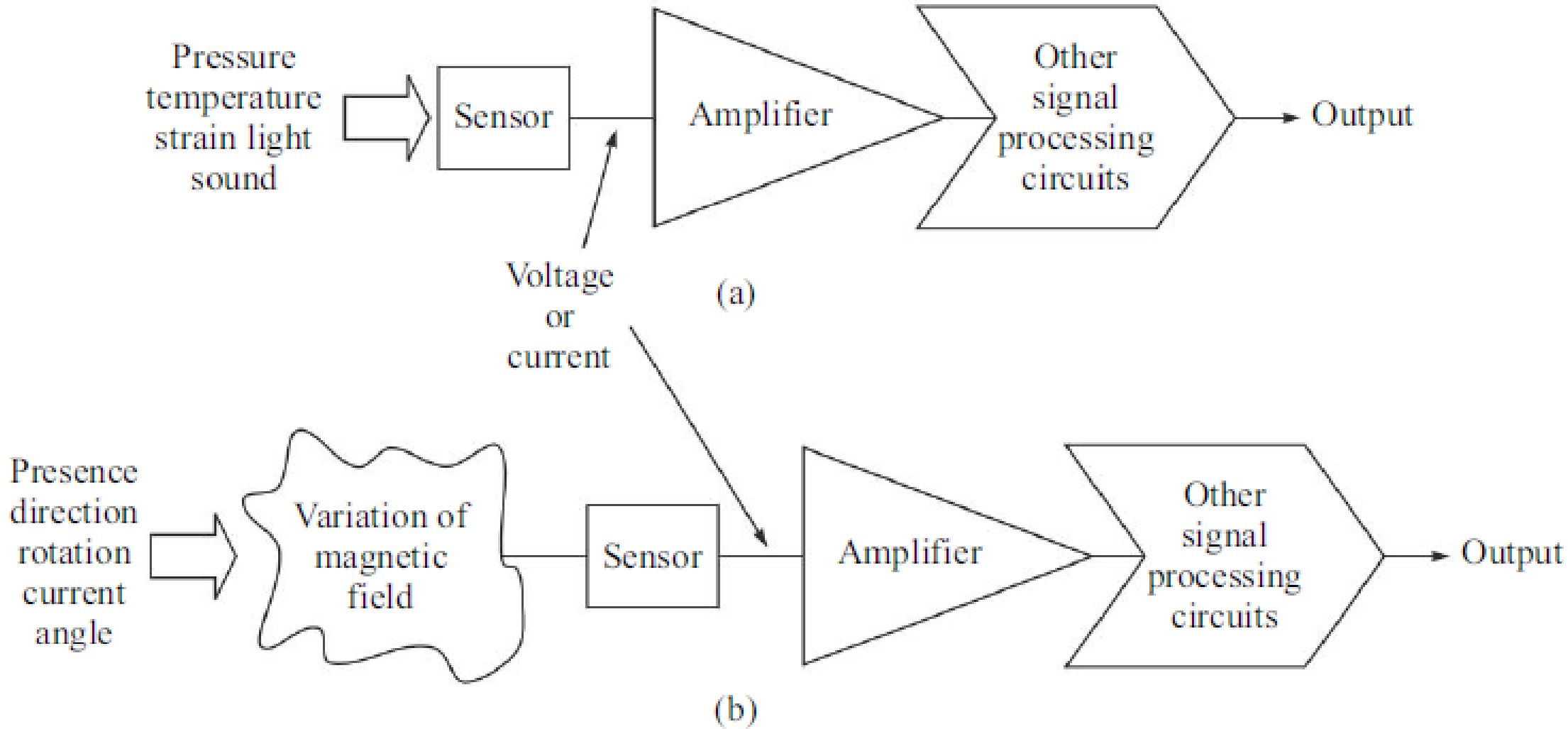

Fig. 8.2 *(a) A typical sensor, (b) An illustration of magnetic sensor*
Courtesy: Honeywell, Inc.

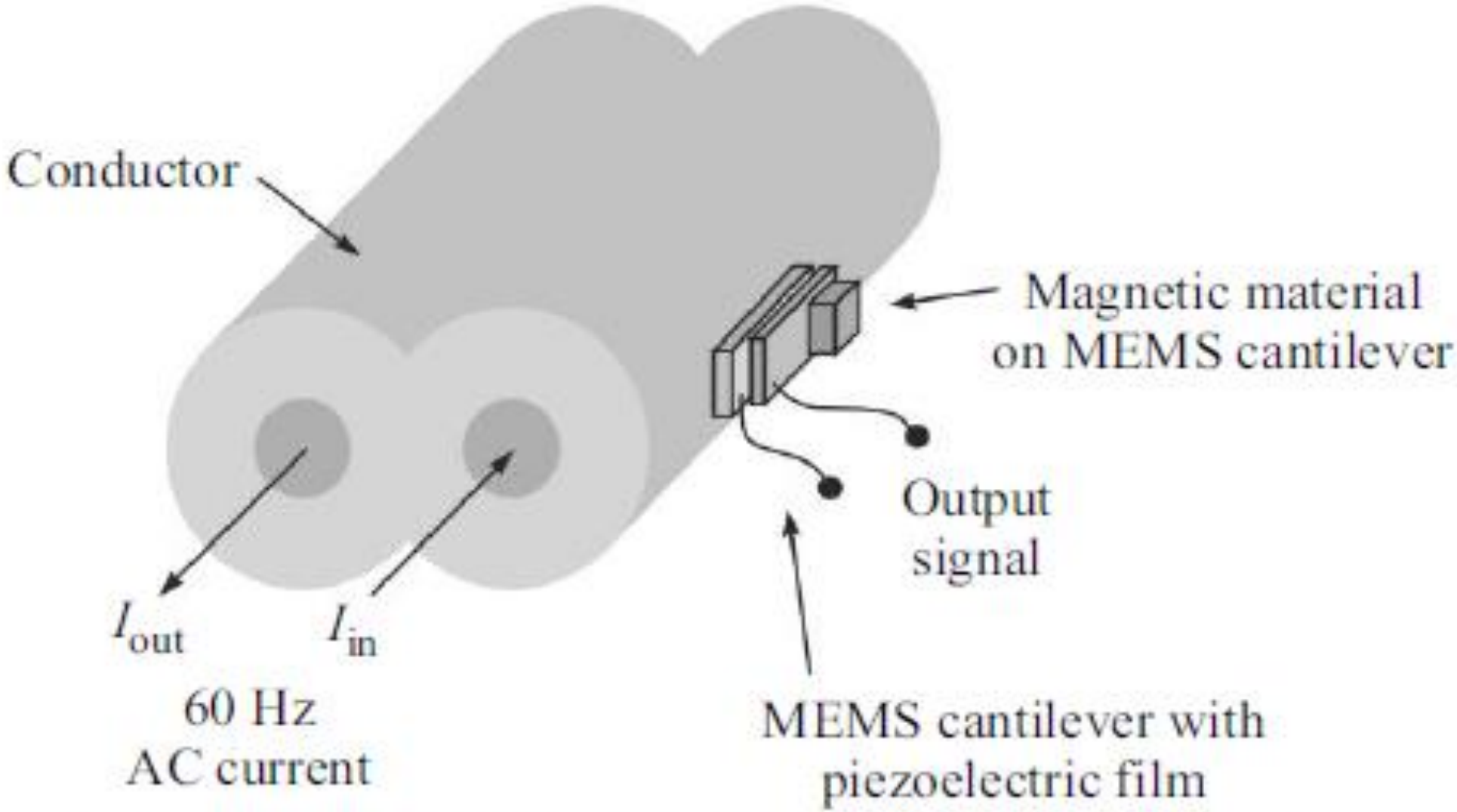

Fig. 8.4 *An MEMS cantilever based magnetic sensor*